Gold-Catalyzed Cascade Cyclization of 2-Alkynyl-N-Propargylanilines by Rearrangement of a Propargyl Group.

AUTHOR(S):

Tokimizu, Yusuke; Oishi, Shinya; Fujii, Nobutaka; Ohno, Hiroaki

Homogeneous Gold Catalysis

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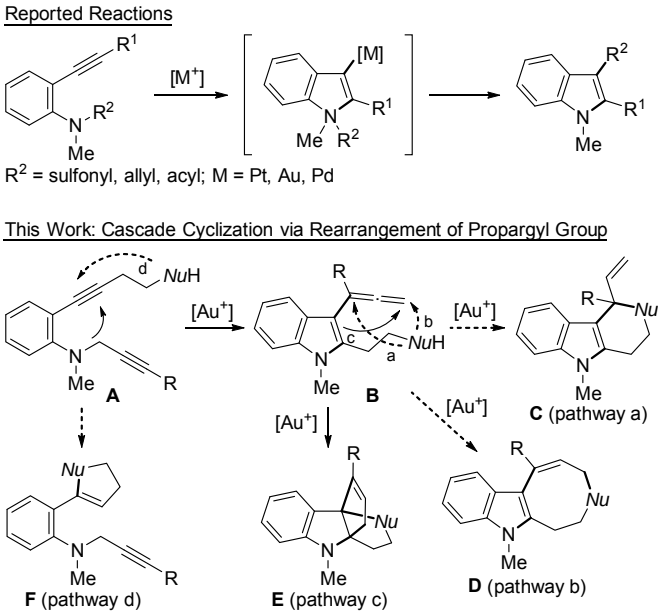
Gold-Catalyzed Cascade Cyclization of 2-Alkynyl-*N*-Propargylanilines via the Rearrangement of a Propargyl Group **

Yusuke Tokimizu, Shinya Oishi, Nobutaka Fujii, and Hiroaki Ohno**

Homogenous gold catalysts have emerged as a powerful tool for the syntheses of natural products and complex molecules.[1] Their π-acidity enables the activation of C−C multiple bonds, which undergo various kinds of transformations.[2] Among the compounds involved in these transformations, allenes are well known as useful building blocks for the construction of cyclic compounds.[2a,c,h,k,m] Despite a variety of efficient reactions including hydroalkoxylation,[3] hydroamination,[3c,4] and hydroarylation[3c,5] having been developed so far, the cyclization reactions of allenes bearing two nucleophilic sites[6] are still limited because of chemoselectivity issues. We propose that indole formation and rearrangement cascade of *N*-propargyl anilines as a promising strategy for the in situ preparation of this class of allenes.

The transition-metal-catalyzed cyclization of *o*-alkynylanilines is an efficient method for the construction of indoles.[7] Recently, several groups have reported that certain substituents on the aniline nitrogen, including sulfonyl,[8] allyl,[9] and acyl groups,[10] can migrate to the C3 position of the indole through indolylmetal intermediates (Scheme 1).[11] Although these reactions are valuable for the preparation of synthetically useful 2,3-disubstituted indole derivatives, there have been no reports in the literature applying this type of migration reaction to cascade cyclizations. As part of our ongoing research focusing on the development of gold-catalyzed cascade reactions for the direct construction of polycyclic heterocycles,[12] we envisaged that the migration of a propargyl group would generate an allene, which could undergo further cyclization reactions. Specifically, we postulated that the use of 2-alkynyl-*N*-propargylaniline **A** as a substrate would lead to the formation of an indole **B** bearing an allenyl group, and the subsequent hydroalkoxylation/amination with an internal nucleophile (pathways a and b) or hydroarylation with indole (pathway c) would produce the corresponding fused indoles **C** or **D**, or indoline **E** in a one-pot manner. The challenge of this strategy is favoring indole formation and migration over cyclization from an internal nucleophile (pathway d). Herein, we describe the gold-catalyzed cascade cyclization of 2-alkynyl-*N*-propargylanilines **A**, in which migration of the propargyl group and hydroarylation of an allene take place to give tetracyclic indolines of type **E**. To the best of our knowledge, this work represents the first example of the migration of a propargyl substituent from the aniline nitrogen atom.



Scheme 1. Transition-Metal-Catalyzed Indole Formation and Rearrangement of *N*-Substituents

Work towards examining the feasibility of this strategy initially focused on the cyclization of *N*-propargylaniline **1a** (Table 1). The reaction of **1a** with 5 mol % of $PPh_3AuCl/AgSbF_6$ in THF at 60 °C gave cyclization product **2a** in 13% yield (entry 1). Among the gold catalysts examined for this reaction, IPrAuCl/$AgSbF_6$ and JohnPhosAuSbF_6·MeCN showed the highest activities, with compound **2a** being isolated in 74% yield in both cases (entries 3 and 4). Several other solvents were tested for the reaction, including toluene, 1,2-dichloroethane (DCE), CH_3NO_2, CH_3CN and dioxane, but all of these solvents led to a decrease in the yield of **2a** (entries 5−9). In contrast, the use of 2-propanol (*i*PrOH) led to an improvement in the yield to 81% (entry 10). The results of an extensive period of screening revealed that the advanced preparation of the gold catalyst (IPrAuSbF_6·MeCN) led to a further improvement in the yield of the desired reaction to 89% (entry 12 vs entry 11). This increase was attributed to avoiding the detrimental effect of the remaining $AgSbF_6$ present in the reaction mixture. Actually, the treatment of **1a** with $AgSbF_6$ led to the decomposition of aniline **1a** (entry 13).

[*] Y. Tokimizu, Dr. S. Oishi, Prof. Dr. N. Fujii, Prof. Dr. H. Ohno
Graduate School of Pharmaceutical Sciences
Kyoto University
Sakyo-ku, Kyoto 606-8501 (Japan)
Fax: (+81) 75-753-4570
E-mail: hohno@pharm.kyoto-u.ac.jp
nfujii@pharm.kyoto-u.ac.jp

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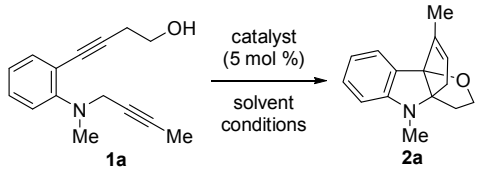
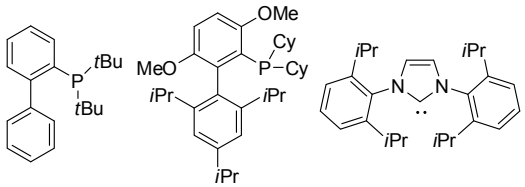
Table 1. Optimization of Reaction Conditions



1a **2a**

entry	catalyst	solvent	conditions	yield (%)[a]
1	$PPh_3AuCl/AgSbF_6$	THF	60 °C, 5 h	13
2	BrettPhosAuSbF$_6$·MeCN	THF	60 °C, 1 h	49
3	IPrAuCl/AgSbF$_6$	THF	60 °C, 1 h	74
4	JohnPhosAuSbF$_6$·MeCN	THF	60 °C, 1 h	74
5	JohnPhosAuSbF$_6$·MeCN	toluene	60 °C, 2 h	41
6	JohnPhosAuSbF$_6$·MeCN	DCE	60 °C, 1 h	16
7	JohnPhosAuSbF$_6$·MeCN	CH_3NO_2	60 °C, 2 h	13
8	JohnPhosAuSbF$_6$·MeCN	CH_3CN	60 °C, 2 h	58
9	JohnPhosAuSbF$_6$·MeCN	dioxane	60 °C, 4 h	58
10	JohnPhosAuSbF$_6$·MeCN	*i*PrOH	60 °C, 2 h	81
11	IPrAuCl/AgSbF$_6$	*i*PrOH	60 °C, 1 h	81
12	IPrAuSbF$_6$·MeCN	*i*PrOH	60 °C, 1 h	89
13	$AgSbF_6$	*i*PrOH	rt, 2 h	dcmp[b]

[a] Isolated yields. [b] Complete consumption of starting material was observed.

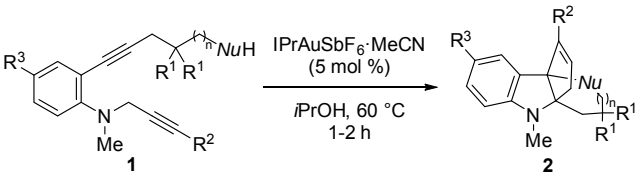


JohnPhos BrettPhos IPr

With the optimized conditions in hand (Table 1, entry 12), we investigated the scope of the reaction using a variety of different substrates (Table 2). Changing the internal nucleophile from an alcohol to a tosylamide or *t*-butylcarbamate (*Nu*H = NHTs or NHBoc) led to the formation of the pyrrolidine-fused indolines **2b** and **2c** in excellent yields (94% and 90%, respectively). The structure of indoline **2b** was confirmed by X-ray crystallography.[13] Aniline **1d** (R^1 = Me) bearing a sterically hindered alcohol also reacted efficiently to give **2d** (83%). Furthermore, anilines **1e** and **1f** bearing a longer carbon tether (n = 1) were smoothly converted to the corresponding indolines with a fused tetrahydropyran ring (**2e** and **2f**, 85% and 91%, respectively). Although aniline **1g** (R^2 = H) bearing a terminal alkyne decomposed under these conditions, anilines **1h** (R^2 = Et) and **1i** (R^2 = Ph) bearing an internal alkyne reacted to give indolines **2h** (87%) and **2i** (92%). Both electron-donating and -withdrawing functional groups were tolerated in the *para* position of the aniline moiety, including the synthetically useful halogen substituents. While methoxy- or methyl-substituted anilines **1j** and **1k** provided indolines **2j** and **2k** in excellent yields (92% and 89%, respectively), Br and F substituted anilines **1l** and **1m** gave the indolines **2l** and **2m** in slightly lower yields (59% and 66%, respectively). The small decrease in the yields of **2l** and **2m** can be rationalized by the relatively low nucleophilicity of the indoles.[14]

Benzyl groups have been reported to migrate in some transition-metal-catalyzed cyclization reactions.[10b,11a] To determine the migratory aptitude of different functional groups towards the C3 position of the indole, aniline **1n** bearing propargyl and benzyl groups was subjected to the optimized conditions (Scheme 2). In this case, the propargyl group exhibited a greater migratory aptitude than the benzyl group to give indoline **2n** as the major product in 73% yield. This result revealed that benzyl-type substituents can be used as nitrogen protecting groups for the current indoline formation.

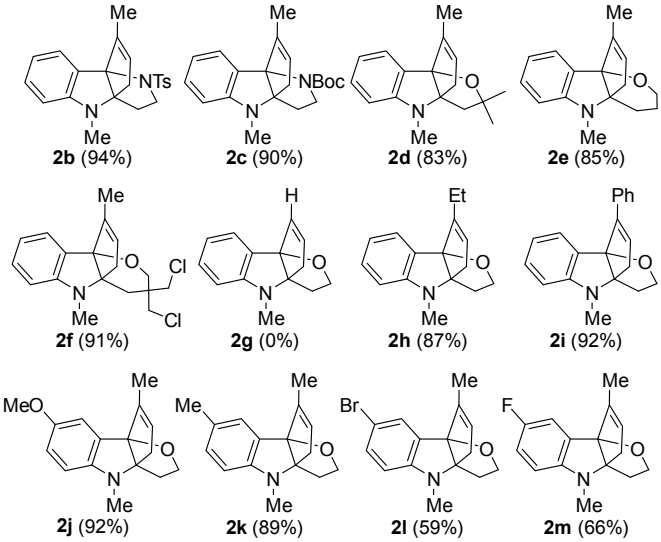
Table 2. Gold-Catalyzed Cyclization of *o*-Alkynyl-*N*-propargylanilines[a]



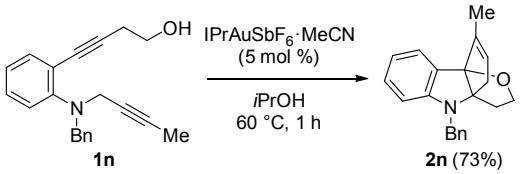
1 **2**

	R^1	R^2	R^3	*Nu*	n
b	H	Me	H	NTs	0
c	H	Me	H	NBoc	0
d	Me	Me	H	O	0
e	H	Me	H	O	1
f	CH_2Cl	Me	H	O	1
g	H	H	H	O	0

	R^1	R^2	R^3	*Nu*	n
h	H	Et	H	O	0
i	H	Ph	H	O	0
j	H	Me	OMe	O	0
k	H	Me	Me	O	0
l	H	Me	Br	O	0
m	H	Me	F	O	0



[a] Isolated yields.

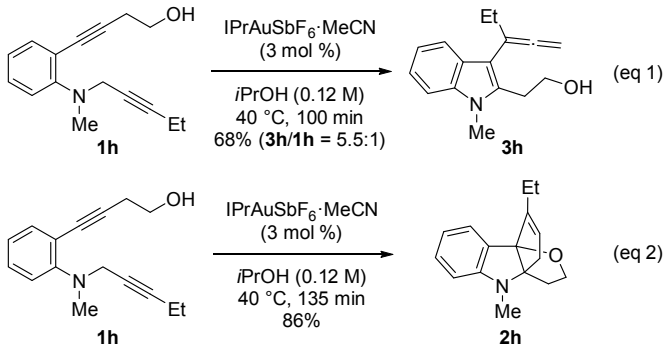


1n **2n** (73%)

Scheme 2. Gold-Catalyzed Cyclization of *N*-Benzylaniline **1n**

Several experiments were subsequently conducted to develop a deeper understanding of the mechanism of this reaction. In the first of these, the reaction of **1h** at 40 °C with 3 mol% of the catalyst was quenched after 100 min to give allene **3h** as a mixture containing a small amount of the starting material (Scheme 3, eq 1; **3h**/**1h** = 5.5:1, 68% combined yield). The low isolated yield of **3h** was attributed to the instability of the allene, which gradually decomposed during purification by column chromatography. When the reaction time was extended to 135 min, indoline **2h** was obtained in 86% yield (eq 2). The reaction of **1h** was then monitored by ^{1}H NMR spectroscopy with 3 mol % of IPrAuSbF$_6$·MeCN in CD_3OD at 40 °C, using $CHCl_2CHCl_2$ as an internal standard (Figure 1). During the first period of the reaction, the conversion of aniline **1h** to allene **3h** proceeded at a constant rate. After 165 min, only 4% of the original aniline **1h** charge remained in the reaction mixture, and **3h** was produced in 95% yield. Interestingly the formation of indoline **2h** was only observed after almost complete consumption of **1h**, with a substantial amount of **2h** having been generated at 215 min. This result clearly demonstrates that the formation of indoline **2h** does

not proceed without the gold catalyst. Furthermore, the gold catalyst selectively promotes the allene formation during the first part of the reaction.



Scheme 3. Gold-Catalyzed Cyclization of *N*-propargylaniline **1h**

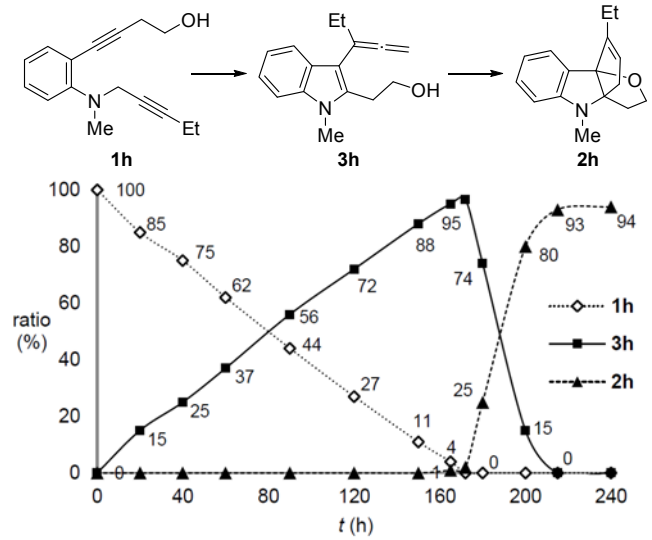
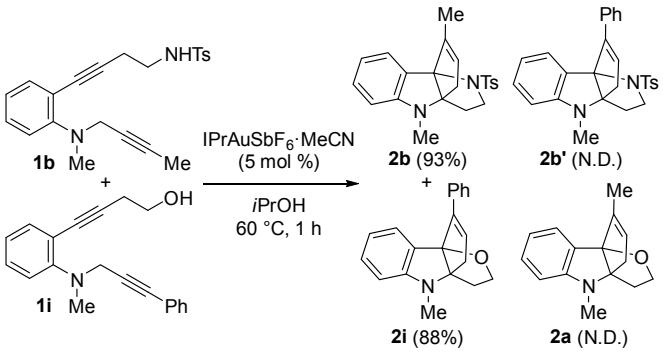


Figure 1. NMR Monitoring of the Reaction of **1h**. *Reaction conditions*: $IPrAuSbF_6·MeCN$ (3 mol %), CD_3OD (0.01 M), $CHCl_2CHCl_2$ (internal standard), 40 °C

A reaction mechanism was proposed based on the results of these experiments (Scheme 4). The reaction begins with the coordination of a cationic gold catalyst to *o*-alkynylaniline **1** to give complex **4**, which undergoes a nucleophilic cyclization reaction from the aniline nitrogen to give indole **5**. The subsequent 1,3-migration of the propargyl group from the nitrogen atom of indolylgold intermediate **5** to the C3 position of the indole gives allene **3**, which is activated by the gold catalyst to give complex **6**. Cyclization of the activated allene, followed by ring expansion of the resulting vinyl gold intermediate **7** gives cationic intermediate **8**, which can be stabilized by the vinylgold moiety as shown in **8'**. The reaction is then terminated by intramolecular nucleophilic addition and subsequent protodeauration of **9** to produce the fused indoline **2**.

The result of the NMR experiment can be rationalized as follows: cycle A is much slower than cycle B,[15] because of the slow nature of the propargyl migration step (Scheme 4), even though the indole formation step (i.e., **4** to **5**) is relatively fast. In other words, the presence of the relatively stable intermediate **5** in cycle A traps the gold catalyst, which therefore prevents cycle B from progressing prior to the completion of cycle A. It was hypothesized that the turnover limiting step of this reaction would be the 1,3-migration of the propargyl group (i.e., **5** to **3**), and this result was supported in part by the isolable character of a related *N*,*N*-dimethyl indolylgold intermediate.[16,17]

A crossover reaction was also conducted to provide further insights into the reaction mechanism (Scheme 5). The exposure of a mixture of anilines **1b** and **1i** to the optimized conditions gave the corresponding indolines **2b** and **2i**, respectively. Notably, the corresponding crossover products **2b'** and **2a** were not detected in the reaction mixture. This result suggests that the migration of the propargyl group occurs in an intramolecular fashion.[18,19]



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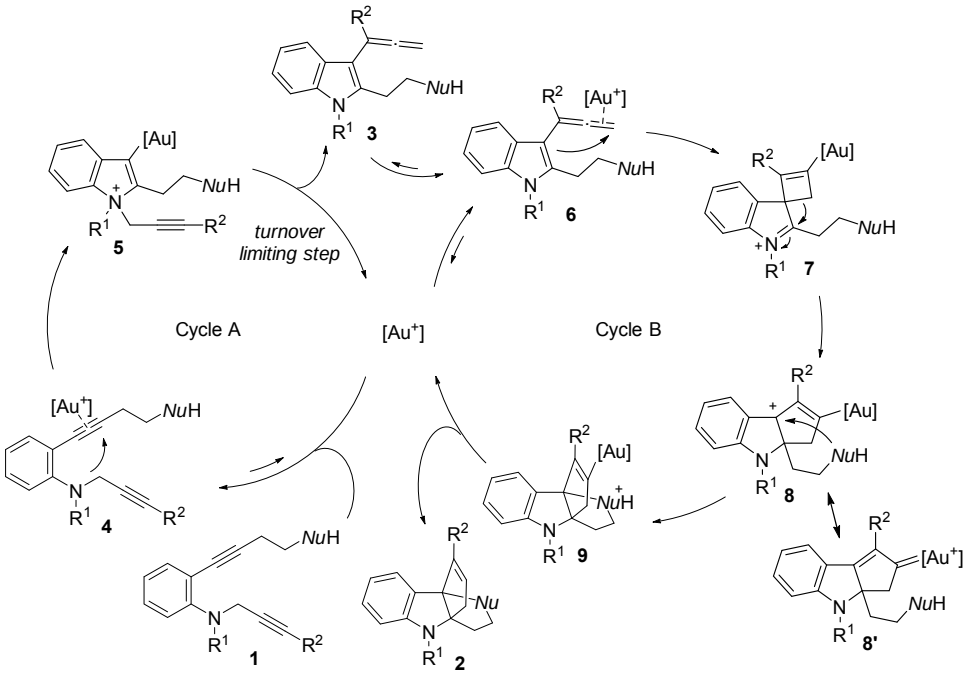

Scheme 4. Postulated Reaction Mechanism

Scheme 5. Crossover Experiment

In conclusion, we have developed a novel gold-catalyzed cascade cyclization reaction of 2-alkynyl-*N*-propargylanilines. The migration of the propargyl group leads to the formation of an indole bearing an allene moiety at the C3 position, which undergoes an intramolecular cyclization reaction with a pendant nucleophile to give a fused indoline. This reaction provides rapid access to fused indolines with three dimensional shapes from starting materials having one dimensional alkyne structures in a single operation, involving the formation of four bonds and three rings. NMR analysis revealed that the formation of the fused indoline only begins after the consumption of the *o*-alkynyl-*N*-propargylaniline starting material. This work could be used in combination with the versatile reactivity of allenes to allow for the synthesis of fused indolines and indoles in a one-pot manner.

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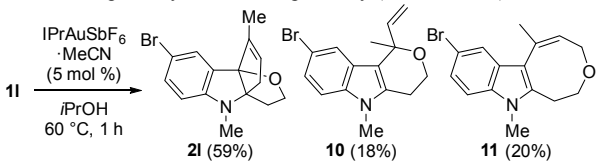
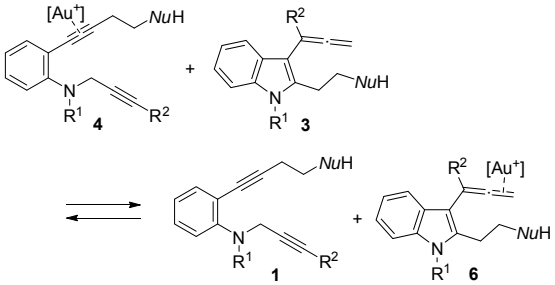
[13] See Supporting Information for the X-ray crystal structure of indoline **2b**.

[14] In the reaction of **1l**, **10** (18%) and **11** (20%) were obtained as the side products, via pathways a and b, respectively (see Scheme 1).



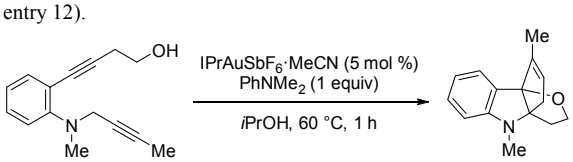
[15] The coordination of a cationic gold catalyst to a simple allene has been reported to be slightly favored over a simple alkyne. This allene preference was contrary to the result observed in the current study, where cycle B only started after the completion of cycle A. A plausible explanation for this observation is the ligand exchange which allows an equilibrium between intermediates **4** and **6** in the reaction, combined with the cyclobutene formation (i.e., **6** to **7**) being slower than that of the indole (i.e., **4** to **5**).



For the coordination energies of a simple allene and an alkyne, see: a) P. H.-Y. Cheong, P. Morganelli, M. R. Luzung, K. N. Houk, F. D. Toste, *J. Am. Chem. Soc.* **2008**, *130*, 4517; for an equilibrium between MeOH and an allene coordinated gold complex, see: b) R. S. Paton, F. Maseras, *Org. Lett.* **2009**, *11*, 2237; see also: c) J. Zhang, W. Shen, L. Li, M. Li, *Organometallics* **2009**, *28*, 3129.

[16] For isolation of a related vinyl gold complex, see: Z. Zeng, R. Kinjo, B. Donnadieu, G. Bertrand, *Angew. Chem.* **2010**, *122*, 954; *Angew. Chem. Int. Ed.* **2010**, *49*, 942.

[17] Another rationalization for the results of the NMR experiment would be that cycle B is hindered by the substrate **1** bearing a basic aniline moiety. However, this possibility is less likely considering the result of the following experiment: the reaction of **1a** in the presence of *N*,*N*-dimethylaniline (1 equiv) under the standard conditions gave the corresponding indoline **2a** in 90% yield, which is essentially the same result as the reaction in the absence of dimethylaniline (89%; Table 1, entry 12).



1a **2a** (90%)

[18] For intramolecular migrations, see refs 10c, 11d, 11g, 11i, and 11m.

[19] For intermolecular migrations, see refs 8, 11c, 11h, and 11k.